

Leaching and persistence of herbicides for kudzu (*Pueraria montana*) control on pine regeneration sites

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Clopyralid, picloram, triclopyr, metsulfuron, and tebuthiuron were applied to control kudzu on four loblolly pine forest regeneration sites during July 1997. Spot treatments were applied to recovering kudzu in June 1998 and June 1999. Soil leachate was monitored for these five herbicides from July 1997 to December 2000. All herbicides were detected in shallow (51–58 cm deep) and deep lysimeters (84–109 cm deep). Clopyralid was not persistent and limited leaching occurred, with residue levels of 0.4 to 2.8 $\mu\text{g L}^{-1}$ in 12 of 102 deep lysimeter samples. Picloram was mobile and persisted at 0.6 to 2.5 $\mu\text{g L}^{-1}$ in shallow and deep lysimeters for at least 10 mo after the initial application. Triclopyr residues were not persistent in shallow lysimeters and remained $< 6 \mu\text{g L}^{-1}$ during the study. Metsulfuron persisted at $< 0.1 \mu\text{g L}^{-1}$ for 182 to 353 d in shallow lysimeters and at $< 0.07 \mu\text{g L}^{-1}$ for 182 to 300 d in the deep lysimeters in various plots. Tebuthiuron peaks in the deep lysimeters ranged from 69 to 734 $\mu\text{g L}^{-1}$ 34 to 77 d after the first spot treatment. In the soil that was essentially a fill area, tebuthiuron residues remained $> 400 \mu\text{g L}^{-1}$ (402–1,660 $\mu\text{g L}^{-1}$) in the shallow lysimeter samples and $> 180 \mu\text{g L}^{-1}$ (181–734 $\mu\text{g L}^{-1}$) in the deep lysimeters throughout a 354-d period that followed the first spot application. When used as part of a forest regeneration program, the relative potentials of the herbicides to move into shallow groundwater were: tebuthiuron $>$ picloram $>$ metsulfuron $>$ clopyralid $>$ triclopyr.

Nomenclature: Clopyralid; metsulfuron; picloram; tebuthiuron; triclopyr; kudzu, *Pueraria montana* (Lour.) Merr. PUEMO; loblolly pine, *Pinus taeda* L. PINTA.

Key words: Groundwater contamination, herbicide dissipation, lysimeter.

Kudzu is an exotic vine that threatens forests in the southeastern United States. It can climb, overtop, and subsequently kill new seedlings or mature trees. Herbicides are commonly used to control kudzu; however, eradication might require retreatment for 3 to 10 yr in young stands and 7 to 10 yr for mature stands (Edwards and Gonzales 1986; Miller 1986; Miller and Edwards 1983; Miller and True 1986). Clopyralid, picloram, triclopyr, metsulfuron, and tebuthiuron exert various degrees of control, depending on soil type, meteorological conditions, herbicide formulation, seasonal application, characteristics of the kudzu stand, and frequency and number of herbicide applications (Kay and Yelverton 1998; Miller 1996). Field residue data for soil or leachate are lacking for all of these herbicides when they are used in actual forest regeneration programs in the Coastal Plain. These data are needed to assess the relative potential for the herbicides to leach into groundwater or to move off-site into sensitive ecological areas of the Coastal Plain in which sandy soils predominate and the groundwater tends to be shallow. This is a particular problem on forest regeneration sites in which a condition of reduced evapotranspiration is created when ground cover is diminished by burning, mechanical processes, or herbicide treatments. Reduced evapotranspiration can increase the volume of water that leaches below the root zone and thereby increases potential herbicide movement to groundwater. As part of an integrated pest management program to control kudzu on forest regeneration areas at the Savannah River Site near New Ellenton, SC, five herbicides were evaluated from the standpoints of herbicide leaching, kudzu control, and plant community de-

velopment. Three herbicide chemical families were represented. This included pyridinecarboxylic acid herbicides (clopyralid, picloram + 2,4-D, and triclopyr), a sulfonylurea herbicide (metsulfuron), and a substituted urea herbicide (tebuthiuron). The picloram + 2,4-D treatment is henceforth referred to as the “picloram” treatment because picloram, not 2,4-D, was the compound of interest in this study. The study was established in 1997 and monitored through 2000. Coincident with the leachate study and in the same treatment plots, Harrington et al. (2003) reported the effect of the herbicides and competition from high-density pine plantings on kudzu control and plant community development. The objectives of the leachate study were (1) to compare the leaching, lateral movement, and persistence of the herbicides and (2) to evaluate leaching relative to potential effects of the herbicide residues on sensitive aquatic species and human health.

Materials and Methods

Study Sites and Treatments

Four study sites (0.4–0.8 ha) that were relatively uniform in kudzu coverage were established at the Savannah River Site (SRS; 33°N, 82°W), a National Environmental Research Park, near New Ellenton, SC. The sites were designated as Burma, Cloverleaf, Home, and Reactor to correspond to the names of nearby road or area features. The sites represented different soil classes and a progression of soil disturbances from a relatively nondisturbed site (Cloverleaf) to a fill site (Reactor). Disturbance was measured as

TABLE 1. Classification of soils and depth of disturbance for each experimental site.

Site	Soil classification	Disturbance (cm of fill above the A-horizon)
Home	Clopyralid plot: Fine, kaolinitic, thermic Plinthic Paleudults (Varina series) Other plots: Loamy, kaolinitic, thermic Arenic Kanhapludults (Ailey series)	None, undisturbed
Burma	Loamy, kaolinitic, thermic Arenic Plinthic Kandiodults (Fuquay series)	18
Cloverleaf	Loamy, kaolinitic, thermic Grossarenic Kandiodults (Troup series)	36–66
Reactor	Udorthent, loamy	104–153

the height of fill above the A-horizon. The soil classes and disturbance were determined on site and are shown in Table 1. Soil samples that were collected on site during soil classification determinations were also analyzed per horizon for texture; pH; cation exchange capacity; percent organic matter; and percent sand, silt, and clay by the Soil and Plant Analysis Laboratory, University of Georgia, Athens, GA.

Each site was divided into six plots of approximately equal area (0.07–0.13 ha), and each plot was randomly assigned a herbicide treatment (five herbicides plus one non-treated check). A pair of lysimeters was installed at depths of 51 to 58 cm (shallow lysimeters) and 84 to 109 cm (deep lysimeters) in each plot. Lysimeters were made from 1-bar high-flow ceramic cups.¹ A solar-powered weather station was installed at the Cloverleaf site to collect precipitation, solar radiation, barometric pressure, relative humidity, wind speed and direction, and temperature data. These data were stored in a data logger on site and periodically downloaded to computers at the Agricultural and Environmental Services Laboratory, University of Georgia.

Whole-plot applications of clopyralid,² picloram,² triclopyr,² metsulfuron,³ and tebuthiuron² were applied from June 30 to July 2, 1997. Table 2 lists the names and application rates of the herbicides. Tebuthiuron granules were applied with a shoulder-mounted cyclone broadcast spreader. The other herbicides were applied with Solo backpack sprayers⁴ that had been calibrated to deliver a volume of 934 L ha⁻¹. Herbicide coverage of the kudzu canopy was enhanced by the addition of 0.25% by volume of a nonionic surfactant.⁵ Tracker Spray Dye⁶ was added to mark the spray swaths. Because the tebuthiuron granules were not dyed, the swath of the application could not be determined exactly, as was the case for the other herbicides. The applicator attempted to avoid plot boundaries so that adjacent plots would not be contaminated with tebuthiuron. This approach resulted in strong control of vegetation in the center of tebuthiuron-treated plots and moderate control along the plot boundaries.

In preparation for planting, sites were broadcast burned

in December 1997. Following the burn, each plot was divided into halves. The half that had not been instrumented with lysimeters was selected for pine plantings. In January 1998, genetically improved loblolly pine seedlings (1+0, groundline diameters ≥ 5 mm) were hand-planted at densities of 0, 1, or 4 seedlings m⁻² in stands of 100 seedlings each. The purpose of the plantings was to induce variable levels of competition that would potentially exclude recovering kudzu (Harrington et al. 2003). Recovering kudzu was treated with spot applications of triclopyr, picloram, or tebuthiuron on June 29, 1998, and June 22, 1999. Because clopyralid and metsulfuron are considered safe to apply over pine seedlings (according to manufacturer's directions), they were broadcast applied on the above dates. A 1-m strip around the perimeter of each plot was defoliated monthly during the growing season with paraquat⁷ to prevent the encroachment of kudzu from adjoining treatment plots or from the surrounding areas.

Sampling and Residue Analysis

Good Laboratory Practice Standards (Code of Federal Regulations 1989) were followed in this study. Lysimeter samples were collected from July 1997 through December 2000. Sampling was conducted weekly for the first month after the initial application, then twice a month for the next 2 mo, then monthly for the remainder of the study. Before sampling leachate from lysimeters, a hand-operated dual vacuum/pressure pump⁸ was used to create a suction of approximately -80 centibars in each lysimeter. The same pump was used to create a pressure of approximately 15 millibars to force water out of a lysimeter and into a pre-labeled 1-L amber glass sample bottle.⁹ Leachate from each lysimeter in a herbicide-treated plot was analyzed only for the herbicide that was applied to the plot in which the lysimeter was located. Leachate from lysimeters in each non-treated check plot was analyzed for all herbicides that were applied in bordering plots. This selectivity in the nontreated check plots was necessary because the volume of water required to analyze a single leachate sample for all herbicides usually exceeded the volume that was collected.

Clopyralid residues were extracted with ether and analyzed by gas chromatography¹⁰ with a ⁶³N electron capture detector and 180 cm by 3 mm i.d. borosilicate glass column packed with 3% OV1.¹¹ Picloram, triclopyr, and metsulfuron residue levels were determined directly from leachate samples (no extractions) by immunoassays.¹² Tebuthiuron residues were extracted with ethyl acetate, dried down at 55 C under 11 to 12 psi of nitrogen on a Zymark Turbo-Vap Concentration Station,¹³ resuspended in 1.0 ml of absolute methanol, and filtered through a 0.45- μ m syringe filter into a 2-ml amber glass chromatography vial. Extracts were an-

TABLE 2. Names and application rates of the herbicides applied to the kudzu plots.

Herbicide				
Commercial name	Common name	Commercial formulation	Application rate	Units
		% ai (ae)	kg ha ⁻¹	
Transline®	Clopyralid	40.9 (31)	0.6	ae
Tordon®	Picloram 2,4-D	10.2 (5.7)	0.9	ae
101M		39.9 (21.2)	3.4	ae
Garlon®4	Triclopyr-ester	61.6 (44.3)	3.5	ae
Escort®	Metsulfuron	60	0.2	ai
Spike®20P	Tebuthiuron	20	4.5	ai

TABLE 3. Method detection limit (MDL) and residue summary data for all herbicides.

	Triclopyr	Clopyralid	Metsulfuron	Picloram	Tebuthiuron
MDL ($\mu\text{g L}^{-1}$)	0.3	0.4	0.025	0.6	0.7
All samples per herbicide					
Total no.	168	194	175	200	217
Total no. with residue ^a	18	30	87	127	204
% with residue	10.7	15.5	49.7	63.5	94.0
Shallow leachate samples					
Total no.	88	92	83	98	108
No. with residue	17	18	53	63	104
% with residue	19.3	19.6	63.9	64.3	96.3
Maximum concentration ($\mu\text{g L}^{-1}$)	5.7	127	2.3	68.5	1660
Deep leachate samples					
Total no.	80	102	92	102	109
Total no. with residue	1	12	34	64	100
% with residue	1.3	11.8	37.0	62.7	91.7
Maximum concentration ($\mu\text{g L}^{-1}$)	0.5	2.8	0.5	15	734

^a Per herbicide, this is the number of leachate samples that contained residues at or above the MDL.

alyzed on a high-performance liquid chromatograph¹⁴ (HPLC) equipped with a reverse phase C-18 ODS Hypersil column (200 by 4.6 mm).¹¹ The mobile phase for the HPLC was water:acetone:methanol (40:40:20, v/v/v).¹⁵

The method detection limit (MDL) was determined for each herbicide (Code of Federal Regulations 1985). Standard reference materials for spiking laboratory blanks were obtained from AccuStandard, Inc.¹⁶ or the manufacturer of each herbicide previously listed.

Statistical Analysis

The study was conducted with the use of a strip-split plot design. The whole plot consisted of experimental plots of six treatments at each site. The effect from depth is considered a stripping effect for each of the six plots because the individual depths cannot be randomly assigned. The time frame of the study was divided into three periods on the basis of herbicide applications. The first period encompassed the time from the whole-plot application to the first spot application period (June 30–July 2, 1997 to June 28, 1998). The second and third periods covered June 29, 1998, to June 21, 1999, and June 22, 1999, to August or December 2000, respectively. The period effect is commonly considered to be a split subplot effect in time. The statistical analyses were conducted with SAS (SAS 1989) software by PROC GLM for unbalanced data. The appropriate error terms were used to test the main effects and interaction terms (Gomez and Gomez 1984).

Results and Discussion

Herbicide Residue Concentrations

Site and application period had no significant effect on herbicide residue concentrations; however, residues were significantly higher in shallow than in deep lysimeters and highest in the tebuthiuron-treated plots (tebuthiuron > picloram > clopyralid = triclopyr = metsulfuron = nontreated check; $P < 0.0001$). Most of the effect of herbicide was caused by relatively higher mean residue levels of tebuthiuron ($131 \pm 213 \mu\text{g L}^{-1}$, $n = 217$) compared with picloram

($2.2 \pm 7.6 \mu\text{g L}^{-1}$, $n = 200$), clopyralid ($1.2 \pm 9.6 \mu\text{g L}^{-1}$, $n = 194$), triclopyr ($0.2 \pm 0.7 \mu\text{g L}^{-1}$, $n = 168$), and metsulfuron ($0.15 \pm 0.35 \mu\text{g L}^{-1}$, $n = 175$).

Clopyralid

Vertical movement of clopyralid was minimal, with most of the residue load in the shallow lysimeters; however, residues were persistent at low levels ($0.4\text{--}1.9 \mu\text{g L}^{-1}$) for 77 to 352 d postapplication. Lateral movement of residues to adjoining nontreated check plots was not evident. Clopyralid does not bind tightly to soils immediately after application, and it is mainly degraded by soil microbes (Pik et al. 1977; Smith and Aubin 1989). In an ecological risk assessment of clopyralid, Rubin (1999b) concluded that the potential for clopyralid to leach is functionally reduced by its relatively rapid degradation in the soil.

Clopyralid residues were detected at or above the MDL of $0.4 \mu\text{g L}^{-1}$ in 15.5% of all leachate samples (Table 3) that contained sufficient volume for analysis. Residues were detected in 19.6% of the shallow leachate samples and in 11.8% of deep leachate samples. The highest residue levels were found in shallow leachate samples (Figure 1A), which contained concentrations of 0.4 to $127 \mu\text{g L}^{-1}$ compared with 0.4 to $2.8 \mu\text{g L}^{-1}$ in the deep leachate samples. Of the shallow leachate samples that contained detectable residues, 12 were $< 3 \mu\text{g L}^{-1}$, 3 were between 3 and $9 \mu\text{g L}^{-1}$, and 1 each were 15, 41, and $127 \mu\text{g L}^{-1}$. Similarly, for the deep leachate samples, six were $< 1 \mu\text{g L}^{-1}$ and residues in the remaining six samples ranged from 1.2 to $2.8 \mu\text{g L}^{-1}$. The highest residue level ($2.8 \mu\text{g L}^{-1}$) in any deep lysimeter sample was detected at the Burma site on the same date (July 30, 1998) that a peak of $127 \mu\text{g L}^{-1}$ was detected in its corresponding shallow lysimeter. The peak levels occurred 30 d after the second clopyralid application and after rain events of 3.1, 2.3, 0.3, 0.7, and 0.5 cm on days 14, 13, 12, 6, and 1, respectively, before drawing a vacuum on the lysimeters. Clopyralid residues were not detected in the nontreated check plots that bordered the clopyralid treatment plots; hence, there was no evidence that residues moved laterally in the soil.

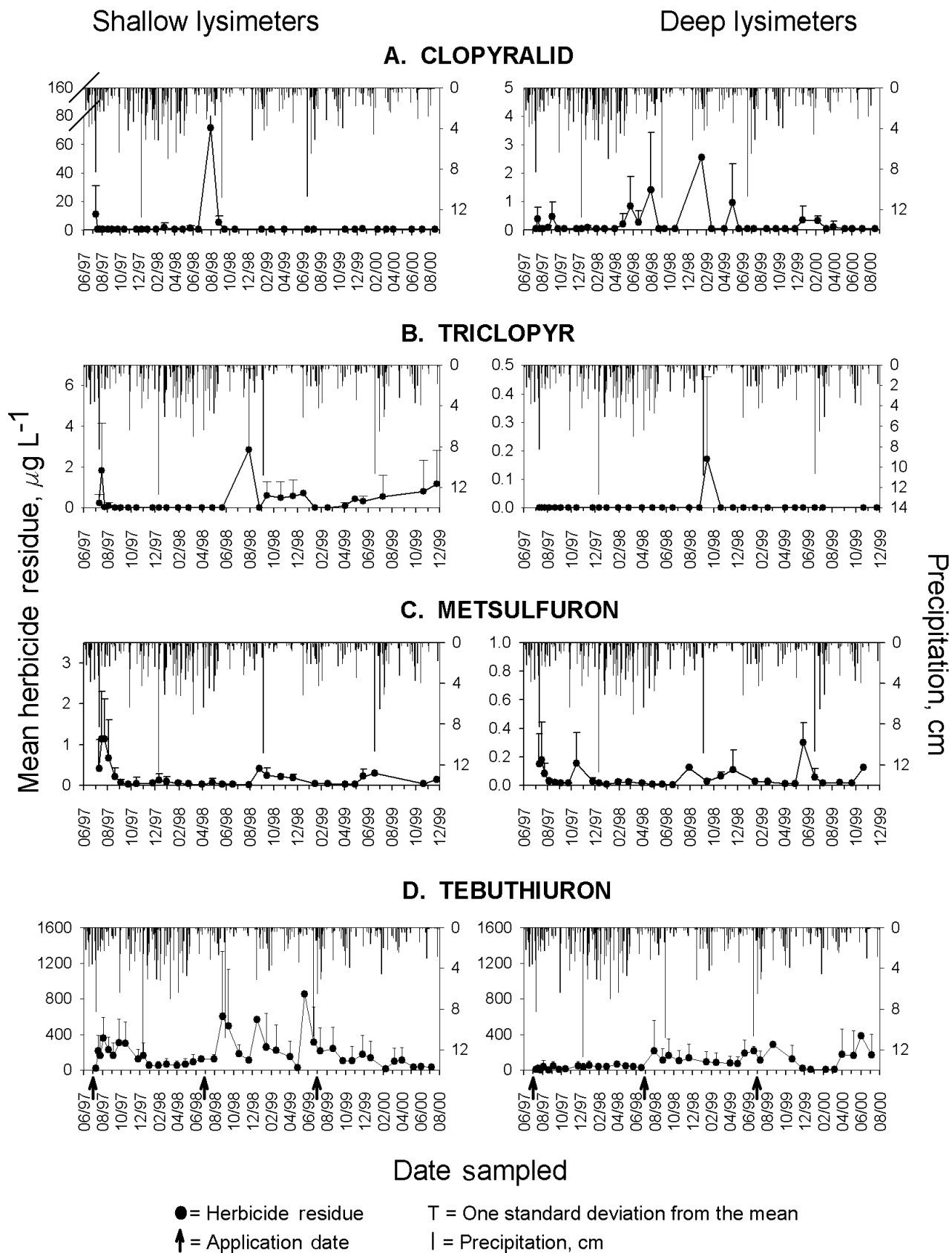


FIGURE 1. Mean residues of clopyralid (A), triclopyr (B), metsulfuron (C), and tebuthiuron (D) in shallow and deep lysimeters in herbicide-treated plots. Missing standard deviation bars indicate that only one lysimeter contained sufficient water volume for analysis on that date or the herbicide residues were below the method detection limit in all samples collected on that date.

Mean residue levels were calculated per sample date and are shown in Figure 1A. Peaks in mean residue levels were not sustained and quickly declined to 1 to 4% of their initial levels within 30 d; however, residues remained above detection limits in some deep and shallow lysimeters for 281 to 352 d after the applications. The last residues detected in shallow and deep lysimeters per application period were 1.5 and 0.6 $\mu\text{g L}^{-1}$, respectively, at 325 and 352 d following the first application; 1.1 and 1.9 $\mu\text{g L}^{-1}$ at 77 and 303 d, respectively, after the second application; and 0.4 and 0.4 $\mu\text{g L}^{-1}$ at 281 and 229 d, respectively, after the third application. Mean residue levels were significantly higher in shallow ($2.4 \pm 13.9 \mu\text{g L}^{-1}$, $n = 92$) than in deep ($0.2 \pm 0.5 \mu\text{g L}^{-1}$, $n = 102$) lysimeters.

The percentage of sampling events that produced leachate samples tended to decrease over time with 83%, 68%, 55%, and 60% in 1997, 1998, 1999, and 2000, respectively. Mean annual lysimeter volume also declined significantly with 1997 ($0.61 \pm 0.37 \text{ L}$) > 1998 ($0.35 \pm 0.38 \text{ L}$) > 1999 ($0.19 \pm 0.28 \text{ L}$) = 2000 ($0.15 \pm 0.28 \text{ L}$). Coincident with these annual declines was the development of a dense blackberry cover (*Rubus argutus* Link, *Rubus cuneifolius* Pursh, and *Rubus trivialis* Michx.) on the clopyralid plots and a parallel decline in precipitation from 166 (1997), 140 (1998), 107 (1999), to 43 cm for January to August 14, 2000. As early as August 1997, a dense, 1.5 to 2.6-m-tall, nearly impenetrable blackberry cover dominated the clopyralid plots and persisted throughout the remainder of the study. During 1997 and 1998, this cover was significantly greater in the clopyralid plots than in the nontreated check or other herbicide-treated plots, and the average percent soil water content during the 1998 and 1999 growing seasons was significantly lower in the clopyralid plots than in the other treatment plots (Harrington et al. 2003). The combination of the dense blackberry cover and less precipitation probably accounted for drier soil and hence less water available for leaching from 1997 onward.

Under the conditions of our study, clopyralid movement was minimal and residues were not a threat to contaminating groundwater at levels that would be a risk to humans or to biological indicator species (Table 4). The human RfD (estimate of a daily oral exposure to the human population

that is likely to be without an appreciable risk of deleterious effects during a lifetime of exposure) for clopyralid is $0.5 \text{ mg kg}^{-1} \text{ d}^{-1}$ (Rubin 1999b). To reach the RfD by consuming water contaminated with the highest level of clopyralid detected in the deep lysimeters, a 68-kg person would need to drink approximately $12,000 \text{ L d}^{-1}$ (Table 4).

Picloram

Picloram was mobile vertically and laterally and persistent at trace to low levels ($0.6\text{--}2.5 \mu\text{g L}^{-1}$) (Figure 2A and 2B). The last residues detected in the deep leachate were 0.6 to 1.6, 1.0 to 1.1, and 0.9 to $2.3 \mu\text{g L}^{-1}$ at 352, 354, and 154 d after the first, second, and third applications, respectively. In the shallow leachate, the last residues detected were 0.6 to 2.5, 1.3 to 2.4, and $0.7 \mu\text{g L}^{-1}$ at 352, 324, and 154 d after the first, second, and third applications, respectively.

Mean residues were significantly higher in shallow ($3.4 \pm 10.6 \mu\text{g L}^{-1}$, $n = 98$) than deep leachate ($1.1 \pm 1.8 \mu\text{g L}^{-1}$, $n = 102$). Residues were detected at or above the MDL ($0.6 \mu\text{g L}^{-1}$) at levels of 0.6 to $68.5 \mu\text{g L}^{-1}$ in 63 of the 98 shallow lysimeter samples and at 0.6 to $15 \mu\text{g L}^{-1}$ in 64 of the 102 deep lysimeter samples; however, residues were below $2.5 \mu\text{g L}^{-1}$ in 95% of the deep leachate samples and 88% of the shallow leachate samples. Of the remaining 12% of the shallow leachate samples, residues ranged from 2.7 to $11.9 \mu\text{g L}^{-1}$ in eight samples, 35.5 to $36.1 \mu\text{g L}^{-1}$ in two samples, and 65.0 to $68.5 \mu\text{g L}^{-1}$ in two other samples.

Picloram leaching was most apparent at the Reactor site, for which a residue level > $11 \mu\text{g L}^{-1}$ (range 11.9– $68.5 \mu\text{g L}^{-1}$) was sustained in the shallow lysimeters during the first 140-d sampling period that followed the first spot treatment. Despite the high residue levels in the shallow lysimeters, picloram residues in the deep leachate from this site did not exceed $5 \mu\text{g L}^{-1}$ during the entire study. Five months after the last spot treatment, residue levels had declined to < $2.6 \mu\text{g L}^{-1}$ in all lysimeters. The highest residue levels followed a rainy period that included an 11-cm rain event. Mean residues were significantly higher at the Reactor site ($6.0 \pm 1.4 \mu\text{g L}^{-1}$, $n = 48$) than at the other sites (Home [$1.2 \pm 1.5 \mu\text{g L}^{-1}$, $n = 51$] = Cloverleaf [$1.0 \pm 2.2 \mu\text{g L}^{-1}$, $n = 51$] = Burma [$0.6 \pm 0.3 \mu\text{g L}^{-1}$, $n =$

TABLE 4. Maximum concentrations of herbicides in deep lysimeters, human RfD values, and 50% lethal concentration toxicity values (LC_{50}) for *Daphnia* (D), bluegill sunfish (BS), and rainbow trout (RT).

Herbicide	Maximum concentration ^a	Human RfD ^b	RfD volume ^c	Toxicity indicator species	LC_{50}
	$\mu\text{g L}^{-1}$	$\text{mg kg}^{-1} \text{ d}^{-1}$	L d^{-1}	mg L^{-1}	
Clopyralid	2.8	0.5 (Rubin 1999b)	12,000	D, BS, RT	232, 125, 103 (Rubin 1999b)
Picloram	15	0.07 (USEPA 2004)	317	D, BS, RT	76, > 24, > 24 (Mayer and Ellersieck 1986; USDA-FS 1984a)
Triclopyr	0.5	0.05 (Rubin 1999a)	6,800	D, BS, RT	113, 148, 117 (USDA-FS 2001)
Metsulfuron	0.48	0.25 (Exttoxnet 2001)	35,000	D, BS, RT	> 150, > 150, > 150 (Exttoxnet 2001)
Tebuthiuron	734	0.07 (USEPA 2002)	6.5 ^e	D, BS, RT	279, 112, 114 (USDA-FS 1986)

^a Maximum concentration detected in the deep lysimeters.

^b Estimate of the daily oral exposure to the human population that is likely to be without an appreciable risk of deleterious effects during a lifetime of exposure.

^c Number of liters of water that a 68-kg person would have to drink daily to reach the human RfD if the water contained the maximum concentration found in the deep lysimeters.

^d Values listed in order for D, BS, and RT. The LC_{50} values are for 48-h tests for D and 96-h tests for BS and RT.

^e This value is for tebuthiuron in the highly disturbed soil of the Reactor site. In undisturbed or lesser disturbed sites (Burma, Cloverleaf, Home), the highest concentration in deep lysimeters was $149 \mu\text{g L}^{-1}$ (RfD volume of 32 L d^{-1}).

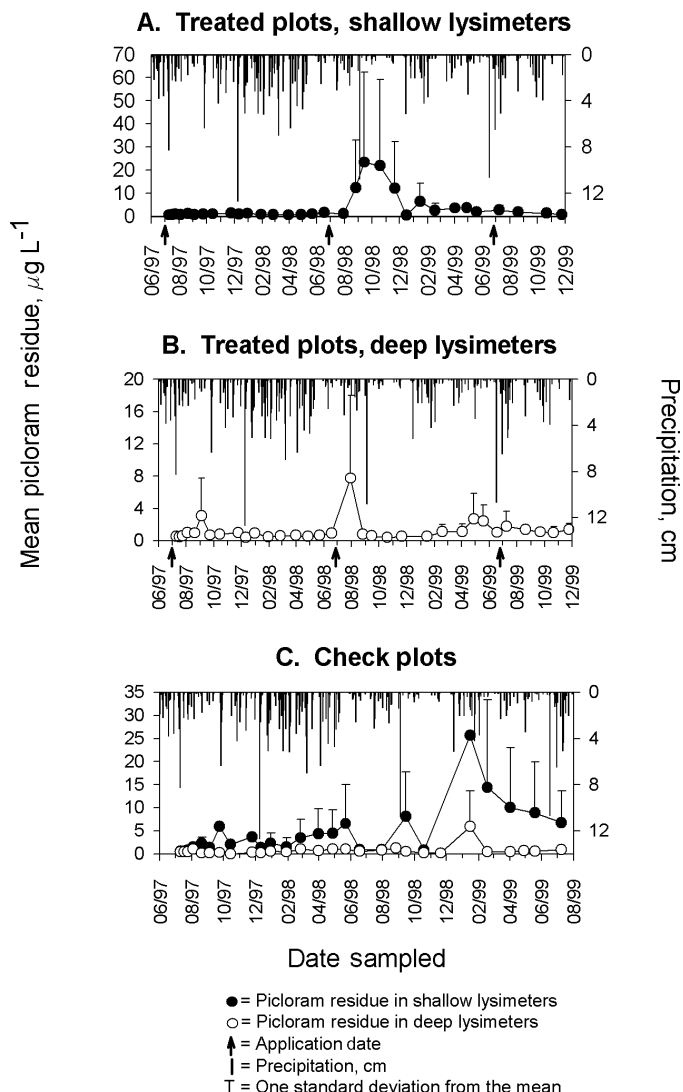


FIGURE 2. Mean picloram residues in (A) shallow and (B) deep lysimeters in the picloram-treated plots and in the check plots (C). Missing standard deviation bars indicate that only one lysimeter contained sufficient water volume for analysis on that date or that picloram residues were below the method detection limit in all samples collected on that date.

50]). Most residue levels in individual shallow and deep lysimeter samples in the Cloverleaf, Home, and Burma sites were similar in that they persisted at 0.6 to 1.6 μg L⁻¹ throughout the study (July 10, 1997, to November 24, 1999), except for a 15-μg L⁻¹-deep leachate sample at the Cloverleaf site (30 d after the first spot treatment).

Picloram moved laterally at least 9 m from the treated plot into the nontreated check plot at the Cloverleaf site and, similarly, at least 21 m at the Home site (Figure 2C). Lateral movement distance was measured from the lysimeters in the nontreated check plot to the closest border of the adjoining picloram plot. Lateral movement was not addressed at the Burma or Reactor sites because the check and picloram plots did not border each other at these sites. In individual samples from the check plots, the highest residue levels were 27.9 and 11.4 μg L⁻¹ in shallow and deep lysimeters, respectively.

Picloram is one of the most mobile of pesticides. One of the major environmental concerns with its use is damage to

nontarget terrestrial plants via leaching, runoff, drift, or the use of contaminated groundwater for irrigation (USEPA 1995). The residue levels in deep lysimeters in our study are not considered hazardous to aquatic species or humans; however, residues persisted at levels that have previously been reported to exert some phytotoxicity to crops in Nebraska (1–4 μg L⁻¹) and West Virginia (0.05–0.4 μg L⁻¹) (Mullison 1985); to tobacco (*Nicotiana tabacum* L.) in North Carolina (0.1 μg L⁻¹) (Sheets 1991); and to tomato (*Lycopersicon esculentum* Mill.), potato (*Solanum tuberosum* L.), and succulent ornamentals (1 μg L⁻¹) (USEPA 1995). If groundwater were contaminated with picloram at the levels that were detected in our study, some phytotoxic effects might be expected in sensitive crop species. This effect could be higher or lower, depending on the recommended rate (0.43–1.68 kg ai ha⁻¹) used by the U.S. Forest Service (Rubin 1999c). To assess the potential effects of herbicides on nontarget plant species, the U.S. Environmental Protection Agency (USEPA) developed a standardized set of plant bioassays for seed germination, seed emergence, and postemergence applications and found that picloram is more toxic to broadleaf plants than to grains or grasses. For the potassium salt of picloram, the lowest reported adverse effect is 1.4×10^{-5} kg ha⁻¹, which is the concentration causing 25% inhibition (EC₂₅) for seed emergence in soybean [*Glycine max* (L.) Merr.] and is about 40,000 times less than the typical U.S. Forest Service application rate of 0.56 kg ai ha⁻¹ (Rubin 1999c). The highest reported NOAEL (no observed adverse effect level) in standard terrestrial plant bioassays is 0.07 kg ha⁻¹ for postemergent applications for wheat (*Triticum aestivum* L.) and seed germination for barley (*Hordeum vulgare* L.). This NOAEL is about eight times less than the typical Forest Service application rate. Thus, picloram is highly toxic to some broadleaf plants such as soybean, and can be toxic to other plant species at typical application rates.

The highest concentration of picloram in any deep lysimeter sample was not a threat to human toxicity or biological indicator species (Table 4). The RfD for picloram is 0.07 mg kg⁻¹ d⁻¹ (USEPA 2004). If a 68-kg person drank water contaminated with 15 μg L⁻¹ picloram, he would have to drink at least 317 L d⁻¹ to meet the RfD.

Triclopyr

Triclopyr was the least mobile of the herbicides tested (Table 3). Because residues were not detected in nontreated check plots that bordered triclopyr-treated plots, there was no evidence that triclopyr moved laterally in the soil. Very limited vertical leaching of triclopyr was apparent. Residues were detected at or above the MDL of 0.3 μg L⁻¹ in one of 80 deep lysimeter samples and in 17 of 88 shallow lysimeter samples. The only deep leachate sample that contained triclopyr (0.5 μg L⁻¹) was collected at the Cloverleaf site on September 14, 1998, after a rain event of 11 cm that had occurred 5 d before applying vacuum to the lysimeters. The mean triclopyr residue in the shallow lysimeters in all sites for that date was 0.31 μg L⁻¹ (range nondetectable to 1.3 μg L⁻¹).

In shallow leachate, residues in individual samples ranged from nondetectable to 5.7 μg L⁻¹, and mean levels remained < 3 μg L⁻¹ for all sampling days (Figure 1B). Of the 17 samples that contained triclopyr residues, nine were below 1.0, three between 1.0 and 2.0, three were between

2.1 and 3.1, and one each was 4.4 and 5.7 $\mu\text{g L}^{-1}$. The sample that contained 5.7 $\mu\text{g L}^{-1}$ was collected in the Burma Site 30 d after the first spot application and after four consecutive daily rainfall events of 4.1, 5.5, 2.0, and 1.2 cm before applying vacuum to the lysimeters.

Triclopyr residues were more persistent during the relatively drier period that followed the first spot application. This was expected because the major mechanism for triclopyr degradation in soil is microbial activity favored by warm, moist conditions (USDA-FS 1984b). Total precipitation declined from 196.3 cm during the whole-plot application period (July 2, 1997–June 28, 1998) to 92.6 cm during the second spot application period (June 29, 1998–June 21, 1999). Total precipitation for the approximately 6 mo after the third application was 55.7 cm. During the wettest period, which occurred after the initial whole plot application, residues were not detected above the MDL after 29 d postapplication. The driest conditions were incurred during the second application period that began with the spot application on June 29, 1998. Most residues during this period were detected within 170 d after the spot treatment; however, one sample contained trace levels (0.4 $\mu\text{g L}^{-1}$) at 324 d postapplication. After the second spot application on June 22, 1999, residues up to 2.3 $\mu\text{g L}^{-1}$ were detected at 145 d postapplication, which was the last sampling date for triclopyr.

Few other field studies have reported triclopyr residues persistent in soil beyond 6 mo after application or at the depths (50–100 cm) reported in our study. Norris et al. (1987) reported triclopyr half-lives of 75 to 81 d in Oregon soils, in which residues of 0.14 mg kg^{-1} and 0.01 mg kg^{-1} were detected in the 0 to 15 cm and 30 to 45 cm depths at 477 d postapplication of 10.1 kg ae ha^{-1} . Residues were not detected between 30 and 90 cm after 180 d. In this same study, and at 356 d after a lower application rate of 3.4 kg ae ha^{-1} , residues of 0.18 mg kg^{-1} and 0.01 mg kg^{-1} were detected in the 0 to 5 and 5 to 15 cm depths, respectively. Residues were not detected at lower depths to 90 cm. A comprehensive review of the environmental fate of triclopyr in soil indicated that triclopyr does not strongly adsorb to soil ($K_d = 0.32$), is potentially mobile (water solubility of 440 mg L^{-1}), and degrades readily, mainly by microbial degradation, with reported half-lives of 10 to 156 d (Ganapathy 1997; Johnson et al. 1995; USDA-FS 1984b; Wauchope et al. 1991). More recent field (including forest soils) and laboratory studies indicate that triclopyr leaching and persistence are very limited and are highly dependent on soil pH and organic matter content (Deubert and Cortes-Real 1986; Neary et al. 1988; Pusino et al. 1994; Rubin 1999a). When triclopyr is used at recommended rates, it is not expected to leach vertically beyond the upper 30 cm of soil or persist (Stephenson et al. 1990; USEPA 1998).

Variations in degradation rates and persistence in literature reports appear to be a function of the formulation used (triclopyr acid, triclopyr butoxyethyl ester [BEE], triclopyr triethylamine salt [TEA], or undisclosed formulation), soil characteristics, and precipitation (natural or simulated) amounts and pattern before collecting soil or leachate. Triclopyr BEE is the active ingredient in the formulation (Garlon 4) that was used in this study. Triclopyr TEA salt is the active ingredient in Garlon 3A. Because the degradation of both forms of triclopyr to triclopyr acid is rapid in soil, most

of the literature has concentrated on the environmental aspects of the parent compound (triclopyr = triclopyr acid).

Our study showed that triclopyr has the potential to be mobile and persistent; however, the maximum residue levels detected in the deep lysimeters would not compromise groundwater quality relative to human health or toxicity to biological indicator species (Table 4). The highest concentration detected in the deep lysimeters is approximately 700 times less than the USEPA's Office of Pesticide Programs estimated health advisory of 350 $\mu\text{g L}^{-1}$ for drinking water (USEPA 1998). Triclopyr is not regulated under the Safe Drinking Water Act; therefore, a maximum contaminant level has not been issued.

In the immunoassays used in this study, two triclopyr degradation products can elicit false positive results for triclopyr. Triclopyr is degraded in soil primarily through microbial activity. The major metabolites are TCP (3,5,6-trichloro-2-pyridinol) and MTP (2-methoxy-3,5,6-trichloropyridine), which Lee et al. (1986) found in soil at 88% and 7 to 15% of applied triclopyr, respectively. Because the least detectable limits to elicit a positive response in our immunoassays were 590 $\mu\text{g L}^{-1}$ for TCP and 0.12 $\mu\text{g L}^{-1}$ for MTP (Strategic Diagnostics Incorporated 1998), it is unlikely that TCP was present in sufficient concentration to elicit a false-positive test because the highest concentration of triclopyr detected in our study was 5.7 $\mu\text{g L}^{-1}$. The tests, however, do not distinguish between MTP and triclopyr, so the results could be a composite of MTP and triclopyr. TCP and MTP are not very mobile and are expected to stay in the top 2.54 to 5.08 cm of soil (Ganapathy 1997; Lee et al. 1986); hence, it is probable that the results of the assays are specifically for triclopyr. Without confirmation from gas chromatography, however, we cannot state absolutely that all of the residue identified as triclopyr was such.

Metsulfuron

The MDL was 0.025 $\mu\text{g L}^{-1}$. Very little metsulfuron residue was detected throughout the 859-d sampling period (Figure 1C), and movement of residue laterally into adjoining nontreated check plots was not evident. Limited leaching occurred, with detectable residues in 37% of the deep leachate samples compared with 64% in the shallow leachate samples (Table 3). Residues were significantly higher in shallow ($0.222 \pm 0.482 \mu\text{g L}^{-1}$, $n = 83$) than in deep ($0.057 \pm 0.123 \mu\text{g L}^{-1}$, $n = 92$) leachate. In individual samples, residue levels ranged from nondetectable to 2.26 $\mu\text{g L}^{-1}$ in shallow leachate and from nondetectable to 0.483 $\mu\text{g L}^{-1}$ in deep leachate. At all sites and following all herbicide applications, residues had declined to less than half of their initial peaks by 41 d postapplication. In shallow leachate, the mean residue levels remained $< 0.7 \mu\text{g L}^{-1}$ from 2 wk after the initial application through the remainder of the study period. In the deep lysimeters, daily mean levels never exceeded 0.3 $\mu\text{g L}^{-1}$ (Figure 1C). Residues were not detected in nontreated check plots that bordered the metsulfuron-treated plots; hence, there was no evidence that metsulfuron residues moved laterally.

Metsulfuron was persistent at trace levels (0.025–0.124 $\mu\text{g L}^{-1}$) in deep leachate and at 0.045 to 0.289 $\mu\text{g L}^{-1}$ in shallow leachate. The last residue levels detected per application period in deep leachate were 0.026, 0.101, and 0.124 $\mu\text{g L}^{-1}$ at 273, 354, and 121 d after the first, second, and

third applications, respectively. Similarly, in the shallow leachate, the last residues detected were 0.045, 0.289, and 0.266 $\mu\text{g L}^{-1}$ at 352, 354, and 155 d after the first, second, and third applications, respectively. Other studies have suggested that metsulfuron has the potential to leach into groundwater at low concentrations; however, "low" has not been defined, and until now, it had not been reported to leach below 60 cm (Extoxnet 2001).

In terms of frequency of occurrence and residue concentration levels, very little metsulfuron was detected during our study. This could reflect the low initial application rate (0.17 kg ai ha⁻¹) and low soil pH (4.3–5.6) in the plots. Pons and Barriuso (1998) reported that abiotic hydrolysis and microbial degradation of metsulfuron were favored at low soil pH (~ 5). Other studies reported half-lives ranging from 14 to 180 d and that degradation rates were positively correlated with microbial biomass and percent organic matter and negatively correlated with soil pH (Berger and Wolfe 1996; Beyer et al. 1988; Hemmamda et al. 1994; Walker et al. 1989; Walker and Welch 1989).

Metsulfuron leached into the deep lysimeters that were 84 to 109 cm deep, thereby indicating a potential to contaminate shallow groundwater. If groundwater that was contaminated with the highest concentration found in the deep lysimeters (0.483 $\mu\text{g L}^{-1}$) were used as an irrigation source to cover 1 ha to a depth of 2.54 cm, then it would generate approximately 120 mg of the herbicide per hectare, which is equivalent to 0.00012 kg ha⁻¹. This rate is below the 0.004 to 0.008 kg ha⁻¹ recommended application rate for use on cereal crops; hence, the residue levels would not be toxic to cereals. The highest concentration of metsulfuron in the deep lysimeters is several magnitudes below levels that would be considered toxic to humans or biological indicator species (Table 4). If metsulfuron leached into groundwater at the highest concentrations found in our study, it would be diluted to undetectable levels.

Tebuthiuron

The MDL for tebuthiuron was 0.7 $\mu\text{g L}^{-1}$. Tebuthiuron was the most persistent and mobile of the herbicides tested. Residues were detected in 94% of all samples collected from the tebuthiuron-treated plots (Table 3).

Residues in the tebuthiuron-treated plots were detected at levels of 1 to 734 $\mu\text{g L}^{-1}$ in 100 of 109 deep leachate samples and at 3 to 1,660 $\mu\text{g L}^{-1}$ in 104 of 108 shallow leachate samples (Table 3). At the end of the first application period (326–353 d postapplication), residues were detected at 18 to 192 $\mu\text{g L}^{-1}$ in individual shallow lysimeters and 10 to 66 $\mu\text{g L}^{-1}$ in individual deep lysimeters across all tebuthiuron-treated plots. Similarly residue levels were 61 to 766 and 13 to 250 $\mu\text{g L}^{-1}$ in shallow and deep lysimeters, respectively, at the end of the second application period (324–354 d postapplication). At the end of the third application period (420 d postapplication), residues were still persistent at 40 to 151 and 9 to 327 $\mu\text{g L}^{-1}$ in shallow and deep lysimeters, respectively.

Mean tebuthiuron residue levels were higher in shallow (179 \pm 264 $\mu\text{g L}^{-1}$, n = 108) than in deep (83 \pm 131 $\mu\text{g L}^{-1}$, n = 109) lysimeters. Across all depths, residues were higher during the second application period (218 \pm 315 $\mu\text{g L}^{-1}$, n = 65) than in either the first (83 \pm 124 $\mu\text{g L}^{-1}$, n = 91) or third (113 \pm 153 $\mu\text{g L}^{-1}$, n = 61) period. Several

reasons are probable for the increase in tebuthiuron residues during this period. The herbaceous cover in the tebuthiuron-treated plots was nearly absent during the second period; hence, the evapotranspiration component of the water budget was low. This reduction in total vegetation cover resulted in a significantly higher average soil water content in the tebuthiuron-treated plots than in the other plots (Harrington et al. 2003). The combination of the soil and plant cover characteristics, and a wet period shortly after the second application (Figure 1D) likely enhanced the movement of tebuthiuron in all sites during this time. Total precipitation decreased from 196.3 cm during the first application period to 92.6 to 102.1 cm during the second and third application periods. Concurrent with this decrease was a significant decrease in lysimeter water volume from 0.50 \pm 0.39 L during the first application period to 0.31 \pm 0.29 L and 0.27 \pm 0.32 L during the second and third application periods, respectively. Mean lysimeter volumes were not significantly different between sites; hence, the volume seemed directly related to total precipitation and not to any specific soil characteristics between the sites. The lower residue levels during the first application period might have been influenced by a dilution effect of the higher precipitation, which resulted in higher lysimeter volumes. Furthermore, some tebuthiuron could have been thermally degraded in the December 1997 burn of the study sites, leaving less tebuthiuron available for leaching during the last 6 mo (January–June 1997) of the first application period. Mean tebuthiuron residue levels declined after the fire (Figure 1D). The decline was noticeable in the shallow lysimeters (50 cm), but not in the deep lysimeters (100 cm). Although the temperature of the burn was not measured, most forestry pesticides (including picloram and triclopyr) are thermally degraded by hot fires > 500 C (Neary et al. 1993).

Soil characteristics favored tebuthiuron movement in the soil. The soils were acid (pH = 4.6–5.6) with low percent organic matter (0.07–2.32). Acidic soils and soils with low percent organic matter favor the movement of nonionic organic compounds such as tebuthiuron that have a low K_d and high water solubility (Chang and Stritzke 1977; Koskinen et al. 1996). Soil characteristics probably also accounted for the significantly higher residues at the Reactor site (254 \pm 345 $\mu\text{g L}^{-1}$, n = 53) than at the Burma site (170 \pm 174 $\mu\text{g L}^{-1}$, n = 56), Home site (81 \pm 91 $\mu\text{g L}^{-1}$, n = 57), or Cloverleaf site (28 \pm 33 $\mu\text{g L}^{-1}$, n = 57). Residue levels at the Reactor site remained > 400 $\mu\text{g L}^{-1}$ (402–1,660 $\mu\text{g L}^{-1}$) in the shallow leachate and > 180 $\mu\text{g L}^{-1}$ (181–734 $\mu\text{g L}^{-1}$) in the deep leachate throughout the entire second application sampling period (July 30, 1998–June 18, 1999), except for a 24- $\mu\text{g L}^{-1}$ sample in one shallow lysimeter. Unlike the other sites, the top soil layer of the Reactor site is a spoil (~ 1.8 m deep) that is continuous past the deep lysimeter depth (1 m). This soil is formed from heterogeneous materials that are the spoil or refuse from excavations and construction operations. The soil has been removed, mixed, and moved and is most commonly associated with well-drained or excessively drained soils (water movement of 15–50 cm h⁻¹). It is characterized by large pores and irregular gaps that can create preferential flow paths. On the basis of soil samples that were collected at the site, the top 0 to 94 cm was classified as a sandy clay loam with pH 4.7, 0.34% organic matter, cation exchange capacity of 4.05, and

32% clay. The 94 to 152 cm depth was classified as a sandy clay with pH 4.6, 0.27% organic matter, cation exchange capacity of 4.99, and 46% clay. Koskinen et al. (1996) reported K_d values of 0.002 to 3.6 L kg⁻¹ for tebuthiuron in six sandy, acid soils (pH 4.10–6.00), with sorption decreasing as the organic matter content decreased. The pH of the Reactor site soils was the lowest of all sites (pH 4.6–4.7 compared with 5.0–5.9 at the other sites), and its clay content was higher than that of the other sites (32–48% compared with 4–22%). The clay type was not identified. Other studies have shown that clay is an important factor in pesticide sorption; however, given the high residue levels in the shallow and deep leachate, it is unclear what effect the clay had on tebuthiuron leaching.

The highest tebuthiuron residue level (734 µg L⁻¹) detected in the deep lysimeters is not a threat to the health of biological indicator species (Table 4); however, its risk in reaching the human RfD is greater than that for the other herbicides used in this study (Table 4). The RfD for tebuthiuron is tentatively set at 0.07 mg kg⁻¹ d⁻¹ (USEPA 2002). To reach the RfD by drinking water contaminated with the highest level of tebuthiuron detected in the deep lysimeters, a 68-kg person would have to consume approximately 6.5 L d⁻¹. Because this volume approaches a typical human consumption of water, it would seem that the concentration detected in our lysimeters could be a threat to human health; however, the actual concentration of tebuthiuron would be diluted in the groundwater. For example, if tebuthiuron at 734 µg L⁻¹ reached groundwater and was diluted by a slight factor of 10, then a 68-kg person would have to consume approximately 65 L d⁻¹ of the diluted water to reach the human RfD. The highest level of tebuthiuron in deep lysimeters was detected at the Reactor site, in which the soil is highly disturbed and characterized by large pores and irregular gaps (Table 1). In the other undisturbed or lesser disturbed sites (Burma, Cloverleaf, and Home), the highest residue levels in deep lysimeters ranged from 70 to 149 µg L⁻¹. To reach the RfD by drinking water contaminated with 149 µg L⁻¹ tebuthiuron, a 68-kg person would have to consume approximately 32 L d⁻¹. On highly disturbed soil sites in which tebuthiuron contamination of shallow groundwater would be of special concern, best management practices should consider not only the residue concentrations that were detected in leachate studies, but also the depth to groundwater and the dilution of those residues if they did reach groundwater.

Implications for Herbicide Use on Forest Regeneration Sites in the Coastal Plain

When used as part of a managed forest regeneration program, the relative potentials of the herbicides to move into shallow groundwater in our study were tebuthiuron > picloram > metsulfuron > clopyralid > triclopyr. None of the herbicides leached to the deepest monitored depth (~ 100 cm) at concentrations that would be potentially hazardous to sensitive aquatic species such as *Daphnia* O.F. Miller, bluegill sunfish (*Lepomis macrochirus* Rafinesque), or rainbow trout (*Oncorhynchus mykiss* Walbaum). In those Coastal Plain areas characterized by sandy soil and shallow groundwater, soil structure should be considered a major factor in managing kudzu. This was the case with tebuthiuron,

for which residue levels that approached the human RfD were detected in deep leachate only from a highly disturbed soil site, but not from undisturbed or lesser disturbed soils. It is likely that the highest herbicide residue levels detected in the deep lysimeters would be diluted by groundwater to nontoxic concentrations relative to human or other animal toxicity.

Another factor in the selection of herbicides to control kudzu is the potential for contaminating groundwater at residue levels that would be toxic to nontarget crops if the water were used for irrigation. In our study, picloram persisted at levels that are toxic to sensitive plants such as tobacco, tomato, potato, and succulent ornamentals. The herbicides used in this study controlled, but did not eradicate, kudzu and induced the development of distinct plant communities. The development of these communities was an important factor in regulating the evapotranspiration component of the water budget and hence should be considered in the selection of herbicides for kudzu control on forest regeneration sites.

Sources of Materials

¹ High-flow ceramic cups, Soil Moisture Equipment Corporation, P.O. Box 30025, Santa Barbara, CA 93105.

² Clopyralid, picloram, triclopyr, and tebuthiuron, E.I. duPont de Nemours & Co., 1007 Market Street, Wilmington, DE 19898.

³ Metsulfuron, Dow AgroSciences, 9330 Zionsville Road, Indianapolis, IN 46269.

⁴ Solo[®] backpack sprayers, Solo, Inc., 5100 Chestnut Avenue, Newport News, VA 23605.

⁵ Timberland 90 surfactant, UAP Timberland LLC, 140 Arkansas Street, Monticello, AR 71657.

⁶ Tracker[™] Spray Dye, Lesco, Inc., 15885 Sprague Road, Strongsville, OH 44136.

⁷ Gramoxene[®] Extra, 2.5% aqueous solution plus 0.125% non-ionic surfactant, Syngenta Crop Protection, P.O. Box 18300, Greensboro, NC 27419.

⁸ Pressure/vacuum hand-pump model 2006G2, Soil Moisture Corporation, P.O. Box 30025, Santa Barbara, CA 93105.

⁹ I-Chem Certified[®] 1-L amber glass Boston round bottles pre-cleaned to meet USEPA standards for pesticide analysis, VWR International, 1310 Goshen Parkway, West Chester, PA 19380.

¹⁰ Tracor Model 222 gas chromatograph, Tremetrics (formerly Tracor), 2215 Grand Avenue Parkway, Austin, TX 78728.

¹¹ GC and HPLC columns were purchased from Supelco, Inc., Supelco Park, Bellefonte, PA 16823.

¹² Immunoassay kits for triclopyr, picloram, and metsulfuron, Strategic Diagnostics, Inc., 111 Pencader Drive, Newark, DE 19702-3322.

¹³ Zymark Turbo-Vap Concentration Station, Zymark Corporation, Zymark Center, Hopkinton, MA 01748.

¹⁴ HPLC chromatograph, Hewlett Packard, Inc., 3000 Hanover Street, Palo Alto, CA 94304-1185.

¹⁵ All solvents (J.T. Baker[®] brand) were purchased from VWR, 1050 Satellite Boulevard, Suwanee, GA 30024.

¹⁶ Analytical standards were purchased from AccuStandards, Inc., 125 Market Street, New Haven, CT 06513.

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Literature Cited

- Berger, B. M. and N. L. Wolfe. 1996. Hydrolysis and biodegradation of sulfonylurea herbicides in aqueous buffers and anaerobic water-sediment systems: assessing fate pathways using molecular descriptors. *Environ. Toxicol. Chem.* 15:1500-1507.
- Beyer, E. M., M. J. Duffy, J. V. Hay, and D. D. Schlueter. 1988. Sulfonylurea herbicides. Pages 118-189 in P. C. Kearney and D. D. Kaufman, eds. *Herbicides: Chemistry, Degradation, and Mode of Action*. Volume 3. New York: Marcel Dekker.
- Chang, S. S. and J. F. Stritzke. 1977. Sorption, movement, and dissipation of tebuthiuron in soils. *Weed Sci.* 25:184-187.
- Code of Federal Regulations. 1985. Definition and Procedure for the Determination of the Method Detection Limit. 40 CFR Ch. 1, Pt. 136, App. B. Pp. 504-506.
- Code of Federal Regulations. 1989. Good Laboratory Practice Standards. 40 CFR Part 160. Federal Register 54 (August 17, 1989). Pp. 34052-34704.
- Deubert, K. H. and I. Corte-Real. 1986. Soil residues of picloram and triclopyr after selective foliar application on utility rights-of-way. *J. Arboric.* 12:269-272.
- Edwards, M. B. and F. E. Gonzales. 1986. Forestry herbicide control of kudzu and Japanese honeysuckle in loblolly pine stands in central Georgia. *Proc. South. Weed Sci. Soc.* 39:272-275.
- Extoxnet 2001. Pesticide Information Profiles. Metsulfuron-Methyl Extoxnet (Extension Toxicology Network housed and maintained at Oregon State University). <http://ace.ace.orst.edu/info/extoxnet/pips/metsulfu.html>.
- Ganapathy, C. 1997. Environmental Fate of Triclopyr. Massachusetts Department of Food and Agriculture. Report. Pp. 1-18. <http://www.cdpr.ca.gov/docs/empm/pubs/fatememo/triclopyr.pdf>.
- Gomez, K. A. and A. A. Gomez. 1984. *Statistical Procedures for Agricultural Research*. 2nd ed. New York: John Wiley. 680 p.
- Harrington, T. B., L. T. Rader, and J. W. Taylor, Jr. 2003. Kudzu (*Pueraria montana*) community responses to herbicides, burning, and high-density loblolly pine. *Weed Sci.* 51:965-974.
- Hemmamda, S., M. Calmon, and J. P. Calmon. 1994. Kinetics and hydrolysis mechanisms of chlorsulfuron and metsulfuron methyl. *Pestic. Sci.* 40:71-76.
- Johnson, W. G., T. L. Lavy, and E. E. Gbur. 1995. Sorption, mobility, and degradation of triclopyr and 2,4-D on four soils. *Weed Sci.* 43:678-684.
- Kay, S. H. and F. H. Yelverton. 1998. Dormant season herbicide treatments for kudzu control. *Proc. South. Weed Sci. Soc.* 51:190-191.
- Koskinen, W. C., D. M. Stone, and A. R. Harris. 1996. Sorption of hexazinone, sulfometuron methyl, and tebuthiuron on acid, low base saturated sands. *Chemosphere* 32:1681-1689.
- Lee, C. H., P. C. Oloffs, and S. Y. Szeto. 1986. Persistence, degradation, and movement of triclopyr and its ethylene glycol butyl ether ester in a forest soil. *J. Agric. Food Chem.* 34:1075-1079.
- Mayer, F. L., Jr., and M. R. Ellersieck. 1986. *Manual of Acute Toxicity: Invertebrates and Data Base for 410 Chemicals and 66 Species of Freshwater Animals*. Washington, DC: U.S. Fish and Wildlife Service Resource Publ. 160. 506 p.
- Miller, J. H. 1986. Kudzu eradication trials testing fifteen herbicides. *Proc. South. Weed Sci. Soc.* 39:276-281.
- Miller, J. H. 1996. Kudzu eradication and management. Pages 34-40 in D. Hoots and J. Baldwin, eds. *Kudzu: The Vine to Love or Hate*. Kodak, TN: Supton Press.
- Miller, J. H. and B. Edwards. 1983. Kudzu: Where did it come from? And how can we stop it? *South. J. Appl. For.* 7:165-169.
- Miller, J. H. and R. E. True. 1986. Herbicide Tests for Kudzu Eradication. Macon, GA: GA For. Res. Paper 65. 10 p.
- Mullison, W. R. 1985. A toxicological and environmental review of picloram. *Proc. West. Soc. Weed Sci.* 38:21-92.
- Neary, D. G., P. B. Bush, C. K. McMahon, R. L. Cantrell, and J. W. Taylor. 1988. Persistence of nine forest pesticides in the surface horizon of a typic quartzipsamment soil of the Ocala National Forest. *Proc. Soil Crop Sci. Soc. Fla.* 47:127-134.
- Neary, D. G., P. B. Bush, and J. L. Michaels. 1993. Fate, dissipation, and environmental effects of pesticides in southern forests: a review of a decade of research progress. *Environ. Toxicol. Chem.* 12:411-428.
- Norris, L. A., M. L. Montgomery, and L. E. Warren. 1987. Triclopyr persistence in western Oregon hill pastures. *Bull. Environ. Contam. Toxicol.* 39:134-141.
- Pik, A. J., E. Peake, M. T. Strosher, and G. W. Hodgson. 1977. Fate of 3,6-dichloropicolinic acid in soils. *J. Agric. Food Chem.* 25:1054-61.
- Pons, N. and E. Barriuso. 1998. Fate of metsulfuron methyl in soils in relation to pedo-climatic conditions. *Pestic. Sci.* 53:311-323.
- Pusino, A., W. Liu, and C. Gessa. 1994. Adsorption of triclopyr on soil and some of its components. *J. Agric. Food Chem.* 42:1025-1029.
- Rubin, L. 1999a. Selected Commercial Formulations of Triclopyr—Garlon 3A and Garlon 4, Risk Assessment—Final Report. Prepared for USDA, Forest Service. Fayetteville, NY: Syracuse Environmental Research Associates document SERA TR 95-22-02-02a. 163 p.
- Rubin, L. 1999b. Clopyralid (Transline)—Final Report. Prepared for USDA, Forest Service. Fayetteville, NY: Syracuse Environmental Research Associates document SERA TR 99-21-11/12-01d. 236 p.
- Rubin, L. 1999c. Picloram (Tordon K and Tordon 22K)—Final Report. Prepared for USDA, Forest Service. Fayetteville, NY: Syracuse Environmental Research Associates document SERA TR 99-21-15-01e. 222 p.
- [SAS] Statistical Analysis Systems. 1989. *SAS/Stat User's Guide*. Version 6, Volume 2, 4th ed. Cary, NC: Statistical Analysis Systems Institute. 1028 p.
- Sheets, T. J. 1991. Comparative effects of soil-applied dicamba and picloram on flue-cured tobacco. N.C. Agricultural Research Service Technical Bull. 295. 26 p.
- Smith, A. E. and A. J. Aubin. 1989. Persistence studies with the herbicide clopyralid in prairie soils at different temperatures. *Bull. Environ. Contam. Toxicol.* 42:670-75.
- Stephenson, G. R., K. R. Solomon, C. S. Bowhey, and K. Liber. 1990. Persistence, leachability, and lateral movement of triclopyr (Garlon) in selected Canadian forestry soils. *J. Agric. Food Chem.* 36:584-588.
- Strategic Diagnostics Incorporated. 1998. *Rapid Assays: Triclopyr. Immunoassay Method Instruction Sheet*. Newark, DE: Strategic Diagnostics.
- [USDA-FS] U.S. Department of Agriculture, Forest Service. 1984a. *Pesticide Background Statements. Volume 1. Herbicides. Picloram. Agriculture Handbook 633*. Washington, DC: U.S. Department of Agriculture. Pp. P1-P87.
- [USDA-FS] U.S. Department of Agriculture, Forest Service. 1984b. *Pesticide Background Statements. Volume 1. Herbicides. Triclopyr. Agriculture Handbook 633*. Washington, DC: U.S. Department of Agriculture. Pp. T1-T62.
- [USDA-FS] U.S. Department of Agriculture, Forest Service. 1986. *Pesticide Background Statements. Volume 1. Herbicides (Supplement): Tebuthiuron. Agriculture Handbook 633*. Washington, DC: U.S. Department of Agriculture. 88 p.
- [USDA-FS] U.S. Department of Agriculture, Forest Service. 2001. *Triclopyr. Herbicide Information Profile*. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. January 8, 2001. 22 p.
- [USEPA] U.S. Environmental Protection Agency. 1995. Reregistration eligibility decision (RED): Picloram. Prevention, Pesticides, & Toxic Substances (7508W). EPA 738-R95-019. Washington, DC: U.S. Environmental Protection Agency. Pp. 9 and 53-55.
- [USEPA] U.S. Environmental Protection Agency. 1998. Registration Eligibility Decision (RED)-Triclopyr. Washington, DC: U.S. Environmental Protection Agency EPA 738-R-98-011, October 1998. 285 p.
- [USEPA] U.S. Environmental Protection Agency. 2002. 2002 Edition of *Drinking Water Standards and Health Advisories*. Washington, DC: Office of Water EPA 822-R-02-038.
- [USEPA] U.S. Environmental Protection Agency. 2004. Picloram. <http://www.epa.gov/iris/subst/0256.htm>.
- Walker, A., E. G. Cotterill, and S. J. Welch. 1989. Adsorption and degradation of chlorsulfuron and metsulfuron methyl in soils from different depths. *Weed Res.* 29:281-287.
- Walker, A. and S. J. Welch. 1989. The relative movement and persistence in soil of chlorsulfuron, metsulfuron methyl, and triasulfuron. *Weed Res.* 29:375-383.
- Wauchope, R. D., A. G. Hornsby, D. W. Gross, and J. P. Burt. 1991. SCS/ARS/CES pesticide properties database: A set of parameter valued for first-tier comparative water pollution risk analysis. Pages 455-470 in D. L. Weigmann, ed. *Pesticides in the Next Decade: The Challenges Ahead. Proceedings, 3rd National Research Conference on Pesticides*. Blacksburg, VA: Virginia Water Research Center, Virginia Polytechnic Institute and State University, November 8-9, 1990.

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